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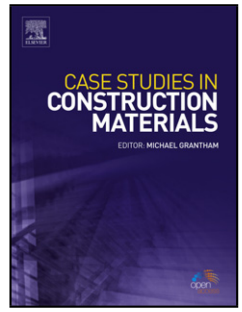

Title: Innovative solutions please, as long as they have been proved elsewhere: the case of a polished lime-pozzolan concrete floor

Author: E.R. Grist K.A. Paine A. Heath J. Norman H. Pinder

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Innovative solutions please, as long as they have been proved elsewhere: the case of a polished lime-pozzolan concrete floor

E R Grist[a,b], K A Paine[b], A Heath[b], J.Norman[c], H Pinder[a]
a. Ramboll, 40 Queen Square, Bristol, BS1 4QP, UK
b. University of Bath, Claverton Down, Bath, BA2 7AY, UK
c. University of Bristol, UK

Corrosponding author:
Ellen Grist.
Ramboll, 40 Queen Square, Bristol, BS1 4QP, UK.
ellen.grist@ramboll.co.uk
+44 (0)1179 295 200

Abstract:

This case-study paper tells the story of the development of a bespoke lime-pozzolan concrete for an innovative project application. In this paper the results of laboratory testing are contextualised by the project-story that steered the research programme. This is an example of a collaborative endeavour to implement a novel low-carbon construction technology in the field.

Evolution of the design in parallel with laboratory testing resulted in the development and specification of a polished lime-pozzolan concrete floor incorporating site-won oolitic limestone aggregate. To the disappointment of the client and the design team, this innovative solution was abandoned at the point the contractor was appointed and changed to a proprietary polished metallic dry shake floor system. The project, a new build extension to a local authority secondary school, was completed in September 2013.

Keywords: innovation, implementation, polished lime-pozzolan concrete, case-study

Highlights:

Innovative new teaching building, incorporating site-won material, sought by school.

Bespoke lime-pozzolan concrete floor screed developed utilising site-won aggregate.

Sample panel of the novel lime-pozzolan concrete polished by specialist sub-contractor.

25% lower embodied-CO_2 and 37% lower embodied energy than vinyl floor finish.

Novel floor specified at end of Stage D but omitted by the client at appointment of main contractor.

Introduction

The construction industry has received on-going criticism for its lack of innovation [1-4] and numerous authors have expounded the specific challenges of innovating in the context of the built environment [5, 6]. One of the unique challenges of innovation in construction is that novel solutions are typically not adopted within organisations, but in the context of one-off projects [7]. Given the one-off nature of construction projects, case studies are an effective tool in researching construction innovation.

Case studies celebrating the successful adoption of novel solutions are clearly valuable; both in promoting cutting-edge technologies and in encouraging others to act similarly [8-11]. Publication of success stories alone, however, might be painting a lop-sided picture of the lived experience of construction professionals and clients in the built environment. Is the 'lack of innovation' in construction not the result of inactivity, but the collective effect of individual project endeavours frustrated by technological, economic or social circumstances? This case study is presented as an example of one such project in which the implementation of an innovative technological solution was unsuccessful despite the design team's aspiration and effort to such an end.

Why was lime-pozzolan concrete considered?

- The school's aspiration was to own an ecological and educational building that would be an inspiration to building users.
- The school's desire to visibly utilise site-won material in the fabric of the new building.
- The school's express interest in research being undertaken by Ramboll and the University of Bath on low-carbon lime-based concretes.
- The discovery of a band of naturally occurring frost-shattered oolitic limestone during the Site Investigation.

The opportunity

The project Site Investigation (SI) was conducted by a geotechnical engineer in April 2011. The structural engineer was present during the excavation to take a sample of the soil, in order to test whether site material was suitable for construction of a rammed earth wall. During the excavation of a number of trial pits, within the footprint of the new building, a 300-700mm thick band of frost-shattered material was encountered from approximately 0.2 metres below the surface. In the trial pit log this material was described as '*loose becoming medium dense beige brown to mid-brown silty sandy GRAVEL and COBBLES of sub-angular oolitic limestone'* (SI report, April 2011).

Figure 1: Frost-shattered oolitic limestone (FSOL) unearthed during the site investigation

Recognising that this naturally occurring site material might also potentially be suitable for use within the fabric of the new building, a sample of this frost-shattered oolitic limestone (FSOL), passed through a 50mm screen, was also bagged for testing in the laboratory. Specifically preliminary testing was undertaken to establish if this site-won material might be suitable as aggregate for a lime-pozzolan concrete.

Preliminary laboratory testing

The particle size distribution (PSD) of the FSOL was measured by sieve analysis in accordance with BS 933-1, 2012 [12]. The results demonstrated that the material was sufficiently well graded that it could be designated as 'all-in aggregate' in accordance with BS EN 12620:2002 [13] and utilised without separating the fractions. On this basis a lime-pozzolan concrete with all-in FSOL aggregate was produced in accordance with BS 1881-125:1986 [14]. An atypically high dosage of superplasticiser (3.2% by mass of binder) was found to be required to produce a flowing concrete. The poor workability of the material was attributed to the large proportion of fine material in the all-in aggregate. Four $100mm^3$ cubes were cast and cured in accordance with BS EN 12390-2:2009 [15]. This lime-concrete had a 28-day compressive strength of around 20 MPa.

What issues were faced and overcome?

Despite the limitations of this early trial and the shortcomings of the resulting lime-pozzolan concrete, this trial was enough to spark the imagination of the design team. Given that the lime-concrete samples were not especially attractive; the appeal of this innovative solution is thought to have been more ideological than aesthetic at this early stage. Recognised as being a *'piece of proper innovation'* this novel material technology embodied the client's design philosophy and it gave the project team the opportunity to be part of a bigger story of technological progress, *'I was very excited that we could be part of something being developed and new'* (School, April 2012). With the design team keen to pursue this novel technology, the Local Authority (the client) commissioned a local contractor to excavate a further tonne of the FSOL (<30mm) from the school site to facilitate further laboratory testing and development.

To improve the concrete mix design the density and aggregate absorption of the FSOL aggregate was measured using the Pyknometer method described in BS EN 1907-7: 2008 [16]. The particle density on a saturated and surface-dried basis (ρ_{ssd}) was calculated to be 2470 kg/m^3. The water absorption after immersion for 24-hours, WA_{24} was measured as being 12.3%, which reflected the porous nature of this oolitic limestone.

It was decided to limit the use of the FSOL to that of 'coarse aggregate' in the anticipation that this would improve the consistence of the fresh lime-pozzolan concrete and reduce the demand for superplastriciser. The FSOL was screened by hand to eliminate particles greater than 28mm and less than 6.3mm in diameter. To preclude the need for a contractor to wash the site aggregate before use, the aggregate screening process was also conducted without washing water and the percentage of fine sand particles, adhering to the larger fragments, was calculated as being around 12% (by mass). This percentage was subsequently factored back into the mix design as a known mass of FSOL fine aggregate. Given that the percentage of fine material retained during screening was expected to depend on the contractors' screening process and the moisture condition of the FSOL aggregate, it was proposed that this adjustment could be recalculated at the point of mixing. The unwashed, screened FSOL was then blended with 34% Marlborough Grit, which was observed to bring the theoretical grading curve of the blended aggregate close to that of carboniferous limestone aggregates utilised in previous lime-pozzolan concrete studies [17].

To investigate the effect of the water-to-binder (w/b) ratio on the compressive strength and visual appearance of the resulting lime-pozzolan concretes, test samples were prepared at three discrete w/b ratios: 0.35, 0.45 and 0.65. The binder consisted of 50% hydraulic lime (NHL5), 40% ground granulated blastfurnace slag (GGBS) and 10% silica fume (SF). The NHL5 used was a natural hydraulic lime manufactured in France and supplied by a specialist lime building-merchant in the UK. The SF was obtained in the form of a slurry, with a SF:water ratio of 50:50 by mass, and conformed to BS EN 13263 [18]. The GGBS conformed to BS EN 15167 [19]. Table 1 details the constituents of each concrete.

Table 1: Lime-pozzolan concrete with FSOL aggregate

The lime-pozzolan concretes were prepared and cured in accordance with standard procedures [14, 15]. Compressive strength was measured in accordance with BS EN 12390-3:2002 [20] at 3, 7 and 28 days and the results are shown in Figure 2.

Figure 2: Compressive strength development of lime-pozzolan concretes with FSOL aggregate

Inspection of the failure surface of a number of the cubes showed that the concrete tended to fail through the aggregate, as opposed to through the lime-pozzolan matrix or at the aggregate-matrix interface. This suggested that the cube strength of these lime-pozzolan concretes was being limited by the capacity of soft site-won FSOL aggregate rather than the lime-binder matrix.

It can be observed from the results in Figure 2 that this lime-pozzolan concrete gained around 75% of its 28-day strength in the first 7 days. Of this, 30-40% of the 28-day strength was attained in the first 3 days after casting.

Constraint based design

With a maximum 28-day compressive strength of 26MPa, and evidence of cubes failing through the aggregate, it was decided that FSOL was inappropriate for use in structural elements of the building, regardless of the choice of binder. The production of higher strength lime-pozzolan concretes was known to be feasible using crushed carboniferous limestone aggregate [21], but for this project the aspiration to demonstrate the use of site-won material favoured the use of the low-strength concrete incorporating the FSOL, in a lower grade application. 28-day cube strengths between 15-26 MPa were deemed sufficient for moderate structural applications such as a ground bearing slab or screed. A polished screed or exposed slab were preferential options as these would be visible to building users, *'you could stand and look at the floor and you'd be stood on the rock, the stone that would have been where you were stood'* (Architect, May 2012). Although there is little recent precedence for polishing lime-concrete floors, historic examples exist, such as the decorative terrazzo floor at the Villa Saraceno, Italy laid in 1612 [22]. Three 200x200x40mm lime-pozzolan concrete prisms were cast and cured in the laboratory before being sent to a specialist concrete polishing contractor for initial polishing trials.

These lime-pozzolan concrete test-panels were diamond polished. The soft aggregate was observed to be slightly eroded by the polishing processes in some places, leading to a slight pitting of the ground surface. The polished lime-pozzolan concrete was then finished with two alternative proprietary sealing products, with the aim of enhancing the performance and durability of the wearing surface. The colour of the finished surface was observed to be dependent on the w/b ratio of the concrete. The lime-pozzolan concrete with a w/b ratio of 0.35 resulted in a concrete with a dark grey-green matrix between the cream-coloured aggregate (see Figure 3 photo (a)), whereas at a w/b ratio of 0.65 the lime-pozzolan matrix was itself also light in colour (see Figure 3 photo (c)). Although the preferred aesthetic divided the opinion of the project team, there was consensus about the attractiveness of the polished samples. The aesthetic appeal of the polished samples not only added weight to the ideological appeal of the novel technology, but provided compelling evidence of the feasibility of this innovative solution, *'the samples looked brilliant so…that was most convincing'* (Architect, May 2012).

Figure 3: Polished lime-pozzolan concrete with FSOL aggregate

Rationale for the innovative solution

The rationale for specification of this innovative lime-pozzolan concrete was the school's desire for a new building with a low environmental impact. Specifically the school's aspiration was to utilise site-won materials and those building materials with a low embodied CO_2 and energy. The embodied CO_2 and energy of the novel lime-pozzolan concrete floor solution was therefore compared with that of two alternative flooring options; a polished Portland cement-concrete (CEMI) floor and a vinyl floor.

The embodied energy and CO_2 associated with the FSOL was assumed to be zero. It was recognised that it would in reality be slightly higher due to mechanical grading and potential transportation for off-site batching. The sub-floor has been excluded from the analysis as it is assumed to be identical in every case. The results of this analysis are shown in Table 2.

Table 2: Embodied CO_2 and energy of a range of potential floor solutions

Although not a full comparative life-cycle analysis (LCA) of these three flooring solutions, which would be beyond the scope of this study, this analysis demonstrated the magnitude of embodied energy and CO_2 savings associated with the choice of flooring system and specifically, in the case of the two alternative polished-concrete floor options, the effect of the choice of binder.

It can be seen from Table 2 that the polished lime-pozzolan concrete option had the lowest embodied carbon and energy of the three flooring options. A polished CEMI concrete floor had a lower embodied energy but a higher embodied CO_2 than a typical vinyl option. In the case of the polished concrete floor options it is worth noting that the steel reinforcing mesh accounts for a significant proportion of the total embodied energy of the overall system. This suggests that lime-pozzolan concretes reinforced with natural fibres, such as sisal, hemp and coir [23, 24] might warrant further investigation in the future development of this technology.

The CO_2 emissions associated with transporting hydraulic lime to the UK were also considered. It was shown that the CO_2 emissions resulting from the necessary transportation of hydraulic lime from France to the UK were minimal (around 40kgCO_2/t) in comparison to those associated with the manufacture of the binder (635kgCO_2/t). Additional transport impacts cannot therefore be used as a legitimate argument for choosing to use a locally available CEMI as an alternative to hydraulic lime.

What happened?

In February 2012 a full specification for the innovative lime-pozzolan floor, which included all the laboratory test results, was issued to six contractors as part of the tender documentation at RIBA Stage D. A week, or so, after the lime-concrete specification was issued the local authority requested its withdrawal; they would not specify the innovative polished lime-concrete floor unless they could see it demonstrated in another school.

Although a non-structural application was pursued, as a low risk application of this novel concrete technology, further testing was recognised as being necessary to verify the performance of the polished lime-pozzolan concrete floor in use. Specifically the slip, chemical and wear resistance of the polished surface were untested at the time at which the decision had to be taken. It was suggested that these aspects of the floor's performance would primarily be determined by the coating applied during the polishing process, but further testing was needed to substantiate this conjecture.

Specifically the slip classification of floors is quantified by coefficient of friction (BS 7976:2002) and surface microroughness testing (performed using a roughness meter) [25]. Adequate slip resistance characteristics were clearly a matter of health and safety and demanded testing. Chemical and wear resistance could have been evaluated in accordance with BS EN ISO 26987:2012 [26] and BS EN 13892 [27] respectively. The heating strategy for the building also included under-floor heating, which necessitated additional system testing as questions remained about the thermal performance of the novel lime-pozzolan concrete. Ideally, this testing would have been conducted in conjunction with the appointed specialist-flooring contractor. Further substantiation of the design was prevented by the project programme, or more accurately by the procurement route, as in reality the floor of the building was not laid for a further sixteen months.

No amount of testing can ever conclusively 'prove' the performance of novel technologies and eliminate the risks associated with their adoption. Rather rigorous testing must persist until decision makers have 'sufficient' evidence. What can't be deduced from this case study is whether or not further substantiation of the novel flooring technology would, or could, have affected the adoption-decision in this case. The problem may have been more systemic. No amount of additional testing would equate to seeing this solution performing in another school, attribute rewarding benefits to the local authority client or undo learning arising from negative experiences of innovation on other projects. When developing bespoke novel solutions, as opposed to new proprietary systems, the need to ascertain client *intentionality* is especially acute.

Conclusions

The innovative lime-pozzolan concrete floor was developed as a key aspect of the design and was significant in reflecting the school's aspirations for the new building. As a result when the bespoke flooring solution was removed from the scheme, the school was extremely disappointed *'I just had this terrible downer about the loss of the limecrete, it was massive, really sort of gloomy*' (School, April 2012). Throughout the design process the focus was on the technical development of this innovative solution, with project-level implementation considered too late in the process to effectively manage the risks accompanying the innovation. Although the design had evolved to minimise the risk, specific concerns about the performance of the new material in use were raised too late for the design to be substantiated.

Whilst the novel lime-pozzolan concrete was being considered as a structural element of the building, design liability lay with the structural engineer. When its proposed use migrated to a non-structural floor finish, responsibility for the design and development fell outside of the structural engineer's remit and professional indemnity insurance. In this case design responsibility was not successfully resolved within the project programme.

Stakeholder buy-in is recognised to be essential in realising innovation [28]. In the case of this project, buy-in from the client-design team was implicitly demonstrated by the actions of individual parties. Specifically, reference was made to the 'polished limecrete floor' in Building Design journal, excavation of additional site material was commissioned to facilitate further testing, samples were reviewed and approved at numerous project meetings, and the limecrete floor was itemised, with an 'extra-over', in the cost plan. Ultimately, however, buy-in was not secured from the one individual who had both the authority and the responsibility to take the final decision. Furthermore this individual had not been engaged in the design process and therefore had not had the same opportunity to evaluate the innovative technology, nor to weigh up the risks and benefits associated with its adoption.

The scale at which the novel technology was to be implemented is also purported to be important. In this case the lime-pozzolan concrete floor was considered central to the scheme and it was specified throughout the ground floor of the building, an area totalling around 150 m^2. Implementation of the new material at a more moderate scale might have been more palatable, although it is recognised that an incidental application may have risked being considered superfluous to the design. Utilisation of the new material in a restricted area was discussed shortly before the lime-concrete was omitted, but no suitable area could be identified. An external slab was also considered as part of the landscaping proposal, but the porous aggregate was deemed highly unlikely to be sufficiently frost-resistant and thus inappropriate for an external application.

Engagement of a contractor and/or specialist-sub contractor early in the design process is anticipated to have been able to address uncertainty about the buildability of the innovative floor system. Commenting in an interview the specialist concrete contractor who had undertaken the polishing trials, is recorded to have said, *'it* *certainly is achievable'* and furthermore *'Every mix is different. Every mix is massively different, from one part of the country to another…so you have little tricks to deal with different places depending on where you are working.'* Such 'real-world' experience is thought to be invaluable in the development of novel technologies and can rarely be offered by academic researchers working in University laboratories.

This project was procured via a Design and Build contract tendered at RIBA Stage D. It is thought that the opportunity to continue the design beyond Stage D might have provided the opportunity for the design team to have conducted a larger scale test to address unanswered questions about the performance of the lime-concrete as a wearing surface.

Given that the lime-concrete specification was withdrawn by the client during the tender period, it is not possible to assess from this case study project whether this innovative aspect of the building would have been driven through to implementation.

Lessons learnt

- Project-level implementation of innovative technologies needs to be considered at the start of the design process, with an implementation strategy developed in parallel with the novel technology itself.
- Clients and designers actively seeking innovative construction solutions should recognise that the pursuance of novelty requires additional project management efforts explicitly focused on the innovative aspects of the project.
- The risks associated with adopting a novel solution need to be explicitly identified so they can be mitigated. All parties should take an 'open book' approach to design risks and be candid with regards to their acceptance of risks.
- Innovative solutions can be informally 'carried' by a project team, but ultimately design liability has to be formally assigned.
- It is crucial that the final decision maker has the opportunity to fully evaluate the novel solution at an appropriate stage.
- The procurement route should be selected to facilitate early contractor engagement.

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Reference

[1] Nam, CH. Toward understanding of product innovation process in construction. Journal of Construction Engineering and Management. 1989;115(4):517-34.
[2] Miozzo, M. Innovation in construction: a European analysis. Edward Elgar Publishing; 2004.
[3] Reichstein, T, Salter, AJ & Gann, DM. Last among equals: a comparison of innovation in construction, services and manufacturing in the UK. Construction Management and Economics. 2005;23(6):631-44.
[4] Drejer, I & Vinding, AL. Organisation,'anchoring' of knowledge, and innovative activity in construction. Construction Management and Economics. 2006;24(9):921-31.

[5] Blayse, AM & Manley, K. Key influences on construction innovation. Construction Innovation. 2004;4(3):143-54.
[6] Dewick, P & Miozzo, M. Networks and innovation: sustainable technologies in Scottish social housing. R&D Management. 2004;34(3):323-33.
[7] Dewick, P & Miozzo, M. Factors enabling and inhibiting sustainable technologies in construction: The case of active solar heating systems. International Journal of Innovation Management. 2002;6(3):257-76.
[8] A Sutton, Black, D, Walker, P & Roberts, M. Low impact material: case studies - hemp lime. BRE. 2011.
[9] A Sutton, Black, D, Walker, P & Brooks, I. Low impact materials: case studies - Cross laminated timber. BRE. 2011.
[10] A Sutton, Black, D, Walker, P, May, N & Brunt, K. Low impact materials: case studies - natural fibre insulation. BRE. 2011.
[11] A Sutton, Black, D, Walker, P & Becket, M. Low impact materials: case studies - Straw-bale. 2011.
[12] BS 933-1. Tests for geometrical properties of aggregates: Determination of particle size distribution — Sieving method. BSI. 2012.
[13] BS EN 12620. Aggregates for concrete. BSI. 2013.
[14] BS EN 1881-125. Testing concrete - methods for mixing and sampling fresh concrete in the laboratory. BSI. 1986.
[15] BS 12390-2. Testing hardened concrete - Making and curing specimens for strength tests. BSI. 2009.
[16] BS EN 1097-7. Tests for mechanical and physical properties of aggregates: Part 7: Determination of the particle density of filler-Pyknometer method. 2008.
[17] Grist, ER, Paine, KA, Heath, A, Norman, J & Pinder, H. Structural and durability properties of hydraulic lime-pozzolan concretes. Submitted to Cement and Concrete Composites. 2013
[18] BS EN 13263-1. Silica fume for concrete: Definitions, requirements and conformity criteria. BSI. 2005.
[19] BS EN 15167-1. Ground granulated blast furnace slag for use in concrete, mortar and grout —Part 1: Definitions, specifications and conformity criteria. BSI. 2006.
[20] BS 12390-3. Testing hardened concrete - compressive strength test of specimens. BSI. 2009.
[21] Grist, ER, Paine, KA, Heath, A, Norman, J & Pinder, H. Lime-pozzolan concretes: addressing project-specific questions. Submitted to Construction and Building Materials. 2013
[22] Holmes, S & Wingate, M. Building with Lime. A practical introduction. 1997
[23] Coutts, RSP. A review of Australian research into natural fibre cement composites. Cement and Concrete Composites. 2005;27(5):518-26.
[24] Brandt, AM. Fibre reinforced cement-based (FRC) composites after over 40 years of development in building and civil engineering. Composite Structures. 2008;86(1):3-9.
[25] HSE. Assessing the slip resistance of flooring: A technical information sheet. Health and Safety Executive. 2012.
[26] BS EN ISO 26987. Resilient floor coverings - determination of staining and resistance to chemicals (ISO 26987:2008). 2012.
[27] BS EN 13892-4. Methods of test for screed materials. Part 4 - Determination of wear resistance -BCA. BSI. 2002.

[28] Akrich, M, Callon, M & Latour, B. The key to success in innovation part I: the art of interessement. International Journal of Innovation Management. 2002;6(2):187-206.

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Figure 1: Frost-shattered oolitic limestone (FSOL) unearthed during the site investigation

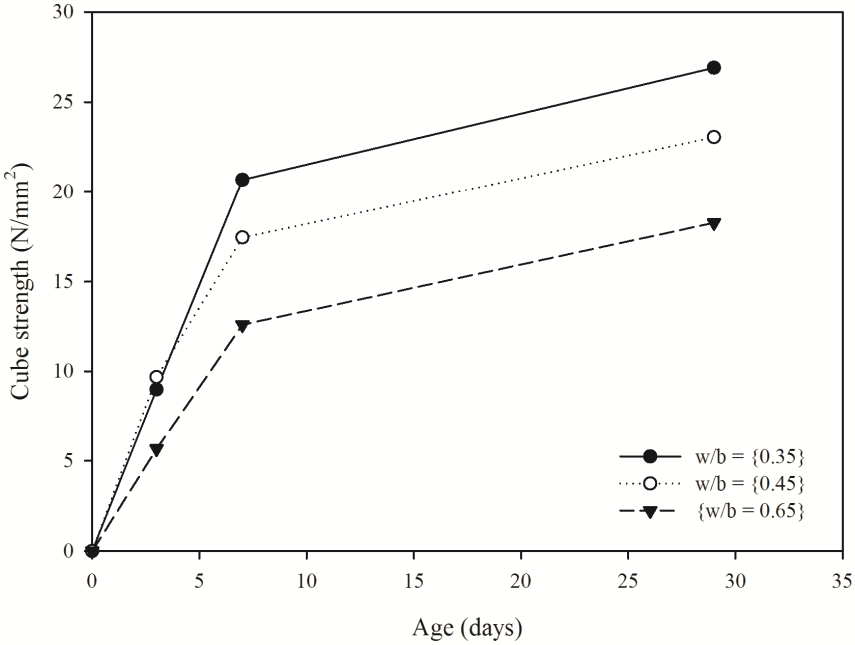
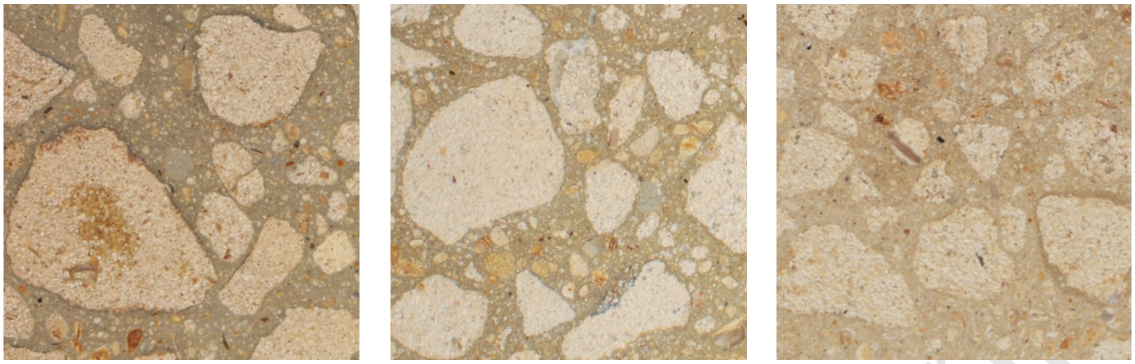


Figure 2: Compressive strength development of lime-pozzolan concretes with FSOL aggregate



(a) w/b = 0.35 (b) w/b = 0.45 (c) w/b = 0.65

Figure 3: Polished lime-pozzolan concrete with FSOL aggregate

Mix	w/b	Water	NHL5	GGBS	SF	FSOL	Marlborough Grit
		kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3
(I)	0.35	190	273	218	55	1280	240
(II)	0.45	190	210	168	42	1360	285
(III)	0.65	190	145	116	29	1370	405

Table 1: Lime-pozzolan concrete with FSOL aggregate

	Thickness	Embodied Energy	Embodied CO_2
	mm	MJ/m^2	$kgCO_2/m^2$
Conventional floor			
Sand-cement screed	65	143	25
Self-levelling screed	3	7	1
Epoxide resin adhesive	-	63	3
Vinyl	2.5	197	7
Sum =	**70.5**	**410**	**36**
Typical polished concrete floor			
CEM I concrete	100	151	32
Reinforcing mesh + spacers	-	112	8
Polishing	-	65	9
Sum =	**100**	**328**	**49**
Typical polished lime-pozzolan concrete floor			
Hydraulic lime concrete	100	81	10
Reinforcing mesh + spacers		112	8
Polishing		65	9
Sum =	**100**	**258**	**27**

Table 2: Embodied CO_2 and energy of a range of potential floor solutions